Searching for $VV \to H \to \tau\tau$ at the CERN LHC

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The production of a neutral, CP even Higgs via weak boson fusion and decay $H \to \tau\tau$ at the LHC is studied for the Standard Model and MSSM, utilizing a parton level Monte Carlo analysis. This channel allows a 5σ observation of a Standard Model Higgs with an integrated luminosity of about 30 fb^{-1}, and provides a direct measurement of the $H\tau\tau$ coupling. For the MSSM case, a highly significant signal for at least one of the Higgs bosons with reasonable luminosity is possible over the entire physical parameter space which will be left unexplored by LEP2.

I. INTRODUCTION

The search for the Higgs boson and, hence, for the origin of electroweak symmetry breaking and fermion mass generation, remains one of the premier tasks of present and future high energy physics experiments. Fits to precision electroweak (EW) data have for some time suggested a relatively small Higgs boson mass, of order 100 GeV [1], hence we have studied an intermediate-mass Higgs, with mass in the $110-150$ GeV range, beyond the reach of LEP at CERN and of the Fermilab Tevatron. Observation of the $H \to \tau\tau$ decay channel in weak boson fusion events at the CERN Large Hadron Collider (LHC) is quite promising, both in the Standard Model (SM) and Minimal Supersymmetric Standard Model (MSSM). This channel has lower QCD backgrounds compared to the dominant $H \to b\bar{b}$ mode, thus offering the best prospects for a direct measurement of a $Hf\bar{f}$ coupling.

Despite weak-boson fusion Higgs production's significantly lower cross section at the LHC (almost one order of magnitude), it has the advantage of additional information in the event other than the decay products' transverse momentum and their invariant mass resonance: the observable quark jets. Thus one can exploit techniques like forward jet tagging [2–4] to reduce the backgrounds. Another advantage is the different color structure of the signal v. the background. Additional soft jet activity (minijets) in the central region, which occurs much more frequently for the color-exchange processes of the QCD backgrounds [5], are suppressed via a central jet veto.

We have performed a first analysis of intermediate-mass SM $H \to \tau\tau$ and of the main physics and reducible backgrounds at the LHC, which demonstrates the feasibility of Higgs boson detection in this channel, with modest luminosity [7]. $H \to \tau\tau$ event characteristics were analyzed for one τ decaying leptonically and the other decaying hadronically. We demonstrated that forward jet tagging, τ identification and reconstruction criteria alone yield an $\approx$2/1 signal-to-background (S/B) ratio; additional large background suppression factors can be obtained with the minijet veto.

In the MSSM, strategies to identify the structure of the Higgs sector are much less clear. For large tanβ, the light neutral Higgs bosons may couple much more strongly to the $T_3 = -1/2$ members of the weak isospin doublets than its SM analogue. As a result, the total width can increase significantly compared to a SM Higgs of the same mass. This comes at the expense of the branching ratio $B(h \to \gamma\gamma)$, the cleanest Higgs discovery mode, possibly rendering it unobservable over much of MSSM parameter space and forcing consideration of other observational channels. Since $B(h \to \tau\tau)$ is instead slightly enhanced, we have examined the τ mode as an alternative /citePRZ.

II. SIMULATIONS OF SIGNAL AND BACKGROUNDS

The analysis uses full tree-level matrix elements for the weak boson fusion Higgs signal and the various backgrounds. Extra minijet activity was simulated by adding the emission of one extra parton to the basic signal and background processes, with the soft singularities regulated via a truncated shower approximation (TSA) [8].

We simulated pp collisions at the CERN LHC, $\sqrt{s} = 14$ TeV. For all QCD effects, the running of the strong-coupling constant was evaluated at one-loop order, with $\alpha_s(M_Z) = 0.118$. We employed CTEQ4L parton distribution functions [9] throughout. The factorization scale was chosen as $\mu_f = \min(p_T)$ of the defined jets, and the renormalization

scale μ_r was fixed by $(\alpha_s)^n = \prod_{i=1}^{n} \alpha_s(p_{T_i})$. Detector effects were considered by including Gaussian smearing for partons and leptons according to ATLAS expectations [10].

At lowest order, the signal is described by two single-Feynman-diagram processes, $qq \to qq(WW, ZZ) \to qqH$, i.e. WW and ZZ fusion where the weak bosons are emitted from the incoming quarks [11]. From a previous study of $H \to \gamma\gamma$ decays in weak boson fusion [12] we know several features of the signal, which we could directly exploit here: the centrally produced Higgs boson tends to yield central decay products (in this case $\tau^+\tau^-$), and the two quarks enter the detector at large rapidity compared to the τ's and with transverse momenta in the 20-80 GeV range, thus leading to two observable forward tagging jets.

We only considered the case of one τ decaying leptonically (e,μ), and the other decaying hadronically, with a combined branching fraction of 45%. Our analysis critically employed transverse momentum cuts on the charged τ-decay products and, hence, some care was taken to ensure realistic momentum distributions. Because of its small mass, we simulated τ decays in the collinear and narrow-width approximations and with decay distributions to π,ρ, a_1 [13], adding the various hadronic decay modes according to their branching ratios. We took into account the anti-correlation of the $\tau^\pm$ polarizations in the decay of the Higgs.

Positive identification of the hadronic $\tau^\pm \to h^\pm X$ decay requires severe cuts on the charged hadron isolation. We based our simulations on the possible strategies analyzed by Cavalli *et al.* [14]. Considering hadronic jets of $E_T > 40$ GeV in the ATLAS detector, they found non-tau rejection factors of 400 or more while true hadronic τ decays are retained with an identification efficiency of 26%.

Given the H decay signature, the main physics background to the $\tau^+\tau^- jj$ events of the signal arises from real emission QCD corrections to the Drell-Yan process $q\bar{q} \to (Z, \gamma) \to \tau^+\tau^-$, dominated by t-channel gluon exchange. All interference effects between virtual photon and Z-exchange were included, as was the correlation of $\tau^\pm$ polarizations. The Z component dominates, so we call these processes collectively the "QCD Zjj" background.

An additional physics "EW Zjj" background arises from Z and γ bremsstrahlung in (anti)quark scattering via t-channel electroweak boson exchange, with subsequent decay $Z, \gamma \to \tau^+\tau^-$. Naively, this EW background may be thought of as suppressed compared to the analogous QCD process. However, the EW background includes electroweak boson fusion, $VV \to \tau^+\tau^-$, which has a momentum and color structure identical to the signal and thus cannot easily be suppressed via cuts.

Finally, we considered reducible backgrounds, i.e. any event that can mimic the Hjj signature of a hard, isolated lepton and missing p_T, a hard, narrow τ-like jet, and two forward tagging jets. Thus we examined $W + jets$, where the W decays leptonically (e,μ) and one jet fakes a hadronic τ, and $b\bar{b} + jets$, where one b decays leptonically and either a light quark or b jet fakes a hadronic τ. We neglected other sources like $t\bar{t}$ events which had previously been shown to give substantially smaller backgrounds [14].

Fluctuations of a parton into a narrow τ-like jet are considered with probability 0.25% for gluons and light-quark jets and 0.15% for b jets (which may be considered an upper bound) [14].

In the case of $b\bar{b} + jj$, we simulated the semileptonic decay $b \to \ell\nu c$ by multiplying the $b\bar{b}jj$ cross section by a branching factor of 0.395 and implementing a three-body phase space distribution for the decay momenta to estimate the effects of lepton isolation cuts. We normalized our resulting cross section to reproduce the same factor 100 reduction found in Ref. [14].

III. STANDARD MODEL ANALYSIS

The basic acceptance requirements must ensure that the two jets and two τ's are observed inside the detector (within the hadronic and electromagnetic calorimeters, respectively), and are well-separated from each other:

$$
\begin{gathered}
p_{T_{j(1,2)}} \geq 40, 20 \text{ GeV}\,, \qquad |\eta_j| \leq 5.0\,, \qquad \triangle R_{jj} \geq 0.7\,, \\
|\eta_\tau| \leq 2.5\,, \qquad \triangle R_{j\tau} \geq 0.7\,, \qquad \triangle R_{\tau\tau} \geq 0.7\,.
\end{gathered} \tag{1}
$$

The Hjj signal is characterized by two forward jets with large invariant mass, and central τ decay products. The QCD backgrounds have a large gluon-initiated component and thus prefer lower invariant tagging jet masses. Also, their τ and W decay products tend to be less central. Thus, to reduce the backgrounds to the level of the signal we required tagging jets with a combination of large invariant mass, far forward rapidity, and high p_T, and τ decay products central with respect to the tagging jets [12]:

$$\eta_{j,min} + 0.7 < \eta_{\tau_{1,2}} < \eta_{j,max} - 0.7\,, \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \tag{2}$$

$$\triangle\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4\,, \qquad m_{jj} > 1\,\mathrm{TeV}\,. \tag{3}$$

Triggering the event via the isolated τ-decay lepton and identifying the hadronic τ decay as discussed in Ref. [14] requires sizable transverse momenta for the observable τ decay products: $p_{T_{\tau,lep}} > 20$ GeV and $p_{T_{\tau,had}} > 40$ GeV. It is possible to reconstruct the τ-pair invariant mass from the observable τ decay products and the missing transverse momentum vector of the event [15]. The τ mass was neglected and collinear decays assumed, a condition easily satisfied because of the high τ transverse momenta required. The τ momenta were reconstructed from the charged decay products' p_T and missing p_T vectors. We imposed a cut on the angle between the τ decay products to satisfy the collinear decay assumption, $cos(\theta_{\ell h}) > -0.9$, and demanded a physicality condition for the reconstructed τ momenta (unphysical solutions arise from smearing effects); that is, the fractional momentum x_τ a charged decay observables takes from its parent τ cannot be negative. Additionally, the x_{τ_ℓ} distribution of the leptonically decaying τ-candidate is softer for real τ's than for the reducible backgrounds, because the charged lepton shares the parent τ energy with two neutrinos. A cut $x_{\tau_l} < 0.75$, $x_{\tau_h} < 1$ proved very effective in suppressing the reducible backgrounds.

Our Monte Carlo predicted a τ-pair mass resolution of 10 GeV or better, so we choose ± 10 GeV mass bins for analyzing the cross sections. Finally, the $Wj + jj$ background exhibits a Jacobian peak in its m_T distribution [14]. A cut $m_T(\ell, \not{p}_T) < 30$ GeV largely eliminates this background.

Using all these cuts together, although not in a highly optimized combination, we expect already a signal to background ratio of 2/1 with a signal cross section of 0.5 fb for $m_H = 120$ GeV.

A probability for vetoing additional central hadronic radiation was obtained by measuring the fraction of events that have additional radiation in the central region, between the tagging jets, with p_T above 20 GeV, using the matrix elements for additional parton emission. This minijet veto reduces the signal by about 30%, but eliminates typically 85% of the QCD backgrounds; the EW Zjj background is reduced by about 50%, indicating the presence of both boson bremsstrahlung and weak boson fusion effects. Because the veto probability for QCD backgrounds is found to be process independent, we applied the same value to the $bb + jj$ background. Table I gives expected numbers of events for 30 fb^{-1} integrated luminosity at the LHC.

It is possible to isolate a virtually background-free $qq \to qqH \to jj\tau\tau$ signal at the LHC, leading to a 5σ observation of a SM Higgs boson with a mere 30 fb^{-1} of data. The expected purity of the signal is demonstrated in Fig. 1, showing the reconstructed $\tau\tau$ invariant mass for a SM Higgs of 120 GeV after all cuts and a minijet veto have been applied. While the reducible $Wj + jj$ and $b\bar{b} + jj$ backgrounds are the most complicated and do require further study, they appear to be easily manageable.

TABLE I. Number of expected events for the signal and backgrounds, for 30 fb^{-1} integrated luminosity, all cuts and application of a minijet veto. Mass bins are ± 10 GeV. Gaussian equivalent significances are stated, based on a proper Poisson statistical analysis. From [7].

m_H(GeV)	Hjj	QCD Zjj	EW Zjj	$Wj + jj$	$b\bar{b}jj$	σ_{Gauss}
110	11.1	2.1	1.4	0.1	0.3	4.1
120	10.4	0.6	0.5	0.1	0.2	5.2
130	8.6	0.3	0.3	0.1	0.2	5.0
140	5.8	0.2	0.2	0.1	0.2	3.9
150	3.0	0.1	0.2	0.1	0.2	2.3

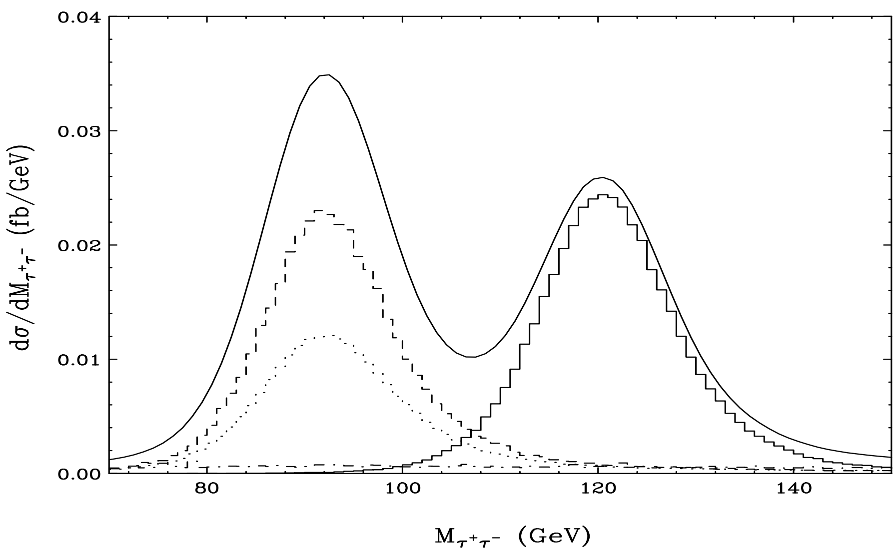

FIG. 1. Reconstructed τ pair invariant mass distribution for the signal and backgrounds after all cuts and multiplication by the expected survival probabilities. The solid line represents the sum of the signal and all backgrounds. Individual components are shown as histograms: the Hjj signal (solid), the irreducible QCD Zjj background (dashed), the irreducible EW Zjj background (dotted), and the combined $Wj + jj$ and $b\bar{b}jj$ reducible backgrounds (dash-dotted).

IV. MSSM ANALYSIS

The production of CP even Higgs bosons in weak boson fusion is governed by the hWW, HWW couplings, which, compared to the SM case, are suppressed by factors $sin(\beta-\alpha), cos(\beta-\alpha)$, respectively [16]. Their branching ratios are modified with slightly more complicated factors. One can simply multiply SM cross section results from our analysis by these factors to determine the observability of $H \to \tau\tau$ in MSSM parameter space. We used a renormalization group improved next-to-leading order calculation, which allows a light Higgs mass up to $\sim$ 125 GeV, and examined two trilinear term mixing cases, no mixing and maximal mixing [6].

Varying the pseudoscalar Higgs boson mass m_A, one finds that m_h,m_H each approach a plateau for the case $m_A \to \infty, 0$, respectively. Below $m_A \sim 120$ GeV, the light Higgs mass will fall off linearly with m_A, while the heavy Higgs will approach $m_H \sim 125$ GeV, whereas above $m_A \sim 120$ GeV, the light Higgs will approach $m_h \sim 125$ GeV and the heavy Higgs mass will rise linearly with m_A. The transition region behavior is very abrupt for large $tan\beta$, such that the plateau state will go to $\sim$ 125 GeV almost immediately, while for small $tan\beta$ the transition is much softer and the plateau state reaches the limiting value via a more gradual asymptotic approach.

With reasonable luminosity, 100 fb^{-1} in the worst case, it will be possible to observe at the 5σ level either h or H decays to τ pairs when they are in their respective plateau region, with the possibility of some overlap in a small region of m_A, as shown in Fig. 2. Very low values of $tan(\beta)$ would be unobservable, but already excluded by LEP2; there should be considerable overlap between this mode at the LHC and the LEP2 excluded region. Furthermore, a parton shower Monte Carlo with full detector simulation should be able to optimize the analysis so that much less data is required to observe or exclude the MSSM Higgs.

V. CONCLUSIONS

We have shown that weak boson fusion production of a Higgs boson with subsequent decay to τ pairs, $qq \to qqH \to jj\tau\tau$, is an excellent observational mode at the LHC, requiring only modest integrated luminosity and allowing direct measurement of the $H\tau\tau$ coupling. This mode also provides a no-lose strategy for seeing at least one of the CP even neutral MSSM Higgs bosons.

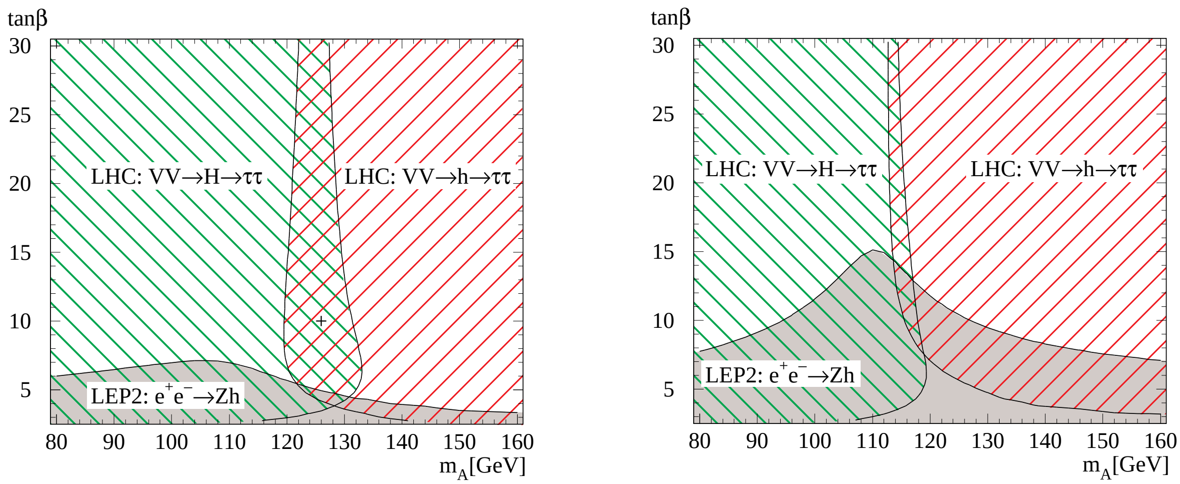

FIG. 2. 5σ discovery contours for $h \to \tau\tau$ and $H \to \tau\tau$ in weak boson fusion at the LHC, with 100 fb^{-1}. Also shown are the projected LEP2 exclusion limits. Results are shown for maximal mixing (left) and no mixing (right). From [6].

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